VOLUMETRIC ANALYSIS ON ASPHALT MIXTURES USING THE COMPUTER PROGRAM PRADO IN COMPARISON WITH LABORATORY DESIGN TESTS

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ABSTRACT

The volumetric analysis of asphalt mixtures mainly makes use of standard laboratory design tests. The Belgian Road Research Centre has developed an analytical computer programme (PRADO) that assists in desktop volumetric design.

The University of Stellenbosch in co-operation with MUCH Asphalt has undertaken desktop volumetric analysis using PRADO on two asphalt mixes, a wearing course mix and an asphalt base mix. The analysis focussed on the determination of an optimal grading and optimal composition of the several aggregate fractions available. It was also used to predict volumetric properties such as voids in mineral aggregate (VMA), voids in mix (VIM) and voids filled with bitumen (VFB). This paper presents the results of these analyses and compares the predicted values with the actual volumetric properties as determined in standard laboratory design tests.

1. STUDY OBJECTIVES

The University of Stellenbosch was approached by MUCH Asphalt to undertake a desktop mix evaluation of a wearing course asphalt mix and an asphalt base mix. The software used for this analysis is the PRADO program developed by the Belgian Road Research Centre. The objective of this analysis is to evaluate the proposed gradings, the composition of aggregate fractions and the volumetric properties of the two mixes.

This paper reports on the results of the standard laboratory design as well as the results of the PRADO analysis. It will in some detail discuss the capabilities and possibilities of the PRADO software and evaluate resemblances and differences between the volumetric properties determined in the laboratory design (Marshall test method) and those calculated by PRADO.

2. STANDARD LABORATORY DESIGN (MARSHALL)

The following two mixes were evaluated in this study:

- Continuously graded asphalt base, maximum stone size 26,5mm (COLTO)
- Medium continuously graded asphalt wearing course mix (TRH8)

The standard laboratory design has been carried out by MUCH Asphalt and the results thereof are summarized below. The compaction energy applied is 2 x 75 blows with the standard Marshall hammer. This level of compaction is standard in South Africa. Information on the bitumen, aggregate and grading has also been provided by MUCH Asphalt.

Proceedings of the 23rd Southern African Transport Conference (SATC 2004) 12 – 15 July 2004
ISBN Number: 1-920-01723-2 Pretoria, South Africa
Proceedings produced by: Document Transformation Technologies cc Conference Organised by: Conference Planners

2.1 Bitumen

For the asphalt base mix a Sapref 40/50 penetration grade bitumen was used, while the TRH8 wearing course mix was produced with a Sapref 60/70 penetration grade bitumen. Following the Marshall laboratory mix design it was determined that the optimum binder content for the asphalt base mix was 4.3% and for the wearing course mix 4.9%.

2.2 Grading

The target grading of the two mixes has been developed by MUCH Asphalt. This is an 'optimum' grading for each of the mixes that has been developed through many years of experience in producing these mixes. The grading of the asphalt base mix is conform the COLTO specifications for an asphalt base mix with a maximum stone size of 26.5mm. The wearing course mix conforms the grading specification of the TRH8 for a medium continuously graded mix.

The grading envelopes of both specifications allow a fair bit of variation in grading. It has been found by MUCH Asphalt that gradings of the best performing mixes are not necessarily exactly in the middle of the grading envelope. The grading curves are shown in Figure 1 and Figure 2.

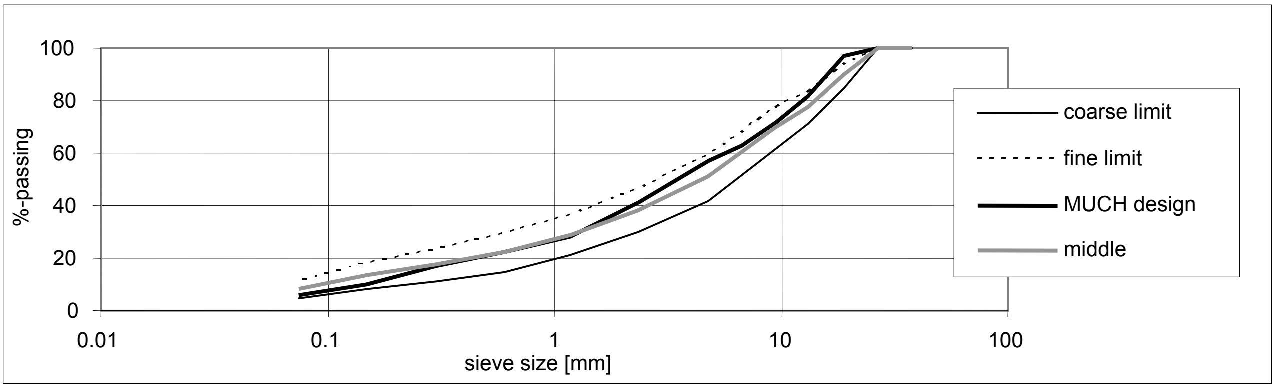

Figure 1. Grading curve of COLTO asphalt base mix (on log scale).

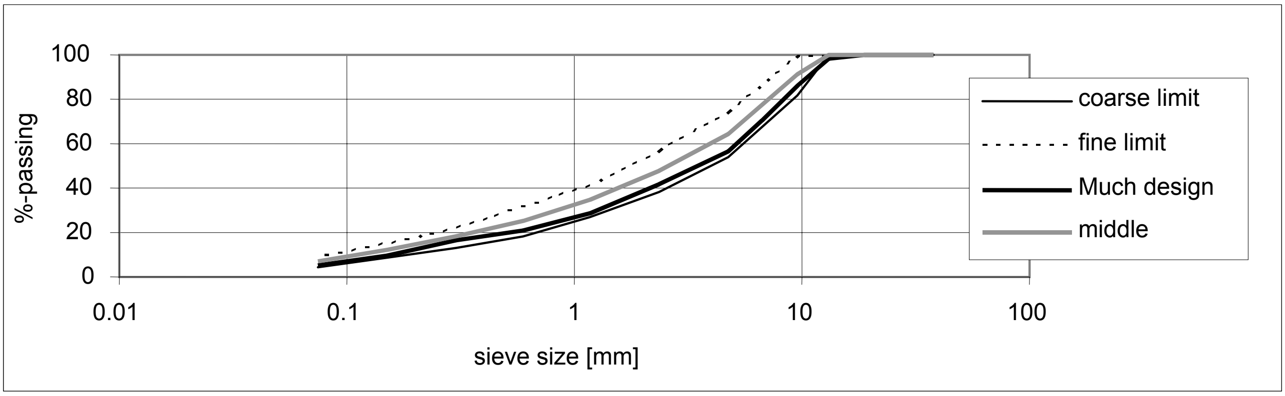

Figure 2. Grading curve of TRH8 wearing course mix (on log scale).

It can be seen that the design grading for the asphalt base mix is on the coarse side of the grading envelope for the smaller particle sizes, while for the larger particles it is more towards the finer side. The 19mm fraction is even slightly outside the grading envelope. The wearing course mix is over the full range of particle sizes towards the coarser limit and differs substantially from the grading that goes through the middle of the envelope.

2.3 Volumetric Design

A standard Marshall mix design has been carried out by MUCH Asphalt. The volumetric properties thereof (VIM, VMA, VFB and f:b (m/m) ratio) are included in Tables 4 and 5.

3. PRADO ANALYSES

3.1 Introduction to PRADO

The PRADO software package can be used as an analytical mix design tool developed by the Belgian Road Research Centre (BRRC). The most recent version of the program operates on a Windows™ platform.

Each mix design study in PRADO consists of 5 components:

1. Characterisation of the binder. Input parameters such as the penetration, softening point, density and viscosity are required;
2. Characterisation of all the different aggregate fractions. For each aggregate component the density, grading and angularity is required. Furthermore for the filler component the Rigden voids of the filler is required;
3. Grading analysis. The grading envelope and the target grading are to be specified. Based on this target grading PRADO determines the optimal aggregate component composition;
4. Mix analysis. Using the input information on the grading and the aggregate components, the voids in the mineral aggregate (VMA) can be determined by PRADO for certain compaction energy levels. The other volumetric parameters such as voids in mix (VIM), volume filled with binder (VFB) and the filler binder ratio’s can be determined by PRADO when either the binder content or the required void content is specified;
5. Mechanical properties such as complex modulus, fatigue and rut resistance can be estimated.

For a detailed description of the methodology behind the PRADO software reference is made to publication A69/79 (OCW). In this study only the first four of the above steps have been carried out as the focus of this project was on the analysis of volumetric parameters.

3.2 Aggregate Components, Composition and Resulting Grading

The aggregate components available for the volumetric design are shown in Table 1. A number of analyses have been carried out for both the asphalt base mix and the wearing course mix. PRADO analyses have been carried out with target gradings being both the middle of the grading envelope (annotated ‘PRADO optimum’) as well as the MUCH Asphalt design grading (annotated ‘PRADO approximation of MUCH design’).

Table 1. Available aggregate components.

Sieve size	Rooikraal					Olifantsfontein		PMD	
	19.0mm	13.2mm	9.5mn	6.7mn	Cr Sand	Washed Cr sand	Unwashed Cr sand	Mine Sand	Hydr. lime
37.5	100	100	100	100	100	100	100	100	100
26.5	100	100	100	100	100	100	100	100	100
19.0	85	100	100	100	100	100	100	100	100
13.2	15	92	100	100	100	100	100	100	100
9.5	3	27	96	100	100	100	100	100	100
6.7	1	2	35	95	100	100	100	100	100
4.75	1	1	3	37	100	99	99	100	100
2.36	1	1	1	1	78	68	72	100	100
1.18	1	1	1	1	49	40	45	100	100
0.600	1	1	1	1	32	26	31	100	100
0.300	1	1	1	1	22	15	21	97	100
0.150	1	1	1	1	14	11	16	39	100
0.075	0.4	0.5	0.4	0.2	7.9	8.5	12.1	10.1	95
BRD	2.975	2.975	2.964	2.973	2.980	2.850	2.850	2.600	2.600

Furthermore the asphalt base mix has been analysed with aggregate components from different sources. In the one analysis the crusher sand source used was the washed crusher sand from the Olifantsfontein quarry (BTB 109-57), while in the second analysis part of the crusher sand fraction came from the Rooikraal quarry and the remaining part was unwashed crusher sand from the Olifantsfontein quarry (BTB 109-57 Olies + RK).

The PRADO grading component determines the optimal aggregate component composition of stockpiles with known narrow gradings based on a binary blending process. This binary process starts blending the two finest aggregate components optimising the specific voids. The so-derived blend is then mixed on a binary basis with the next finest grading component and so on until all grading components have been blended in. The final blend has a grading as closely as possible approaching the target grading. This process is in more detail described by Smit (2002).

The MUCH Asphalt design mix compositions as well as the PRADO calculated compositions are given in Table 2 below. The several compositions lead to gradings that are summarised in Table 3.

Table 2. Aggregate component composition.

Design	Rooikraal					Olifantsfontein		PMD	
	19.0	13.2	9.5	6.7	cr sand	washed cr sand	unw.cr sand	Mine sand	Hydr. lime
MUCH BTB 109-57 design	20%	12%	8%	5%	0%	45%	0%	9%	1%
PRADO approx. MUCH BTB 109-57 design	20.1%	11.6%	8.1%	6.7%	0.0%	43.4%	0.0%	8.0%	1.5%
PRADO optimum BTB 109-57	25.0%	5.2%	19.7%	0.0%	0.0%	38.8%	0.0%	7.1%	4.3%
MUCH BTB 109-57 O+RK design	17%	16%	10%	6%	24%	0%	21%	5%	1%
PRADO approx. MUCH BTB 109-57 O+RK design	16.8%	16.0%	10.2%	6.1%	24.1%	0.0%	20.9%	5.0%	1.0%
MUCH TRH8 design	0%	18%	17%	14%	45%	0%	0%	5%	1%
PRADO approx. MUCH TRH8 design	0.0%	18.5%	18.2%	12.0%	46.0%	0.0%	0.0%	4.5%	0.8%
PRADO opt. TRH8	0.0%	11.9%	16.5%	12.1%	51.8%	0.0%	0.0%	5.1%	2.6%

Table 3. Resulting gradings according to PRADO.

Sieve size [mm]	COLTO BTB 26.5mm					TRH8 medium continuously graded w.c.		
	MUCH BTB 109-57 design	PRADO approx. MUCH BTB 109-57 design	PRADO opt. BTB 109-57	MUCH BTB 109-57 O+RK design	PRADO approx. MUCH BTB 109-57 O+RK design	MUCH TRH8 WC Design	PRADO approx. MUCH TRH8 design	PRADO opt. TRH8
37.5	100	100	100	100	100	100	100	100
26.5	100	100	100	100	100	100	100	100
19.0	97	97.0	96.4	97	97.5	100	100	100
13.2	82	82.0	79.0	84	84.7	99	99	99
9.5	72	72.0	72.1	71	72.1	86	86	91
6.7	63			61		71	69	77
4.75	57	57.0	52.2	54	54.6	57	57	65
2.36	41	40.8	39.5	40	41.0	42	42	48
1.18	28	28.5	28.5	28	28.4	29	29	33
0.600	22			21		21	21	25
0.300	17	16.9	18.6	16	16.5	16	16	19
0.150	11	10.6	12.6	10	10.6	10	10	13
0.075	6	6.3	8.6	6	6.2	5	5	7

The following has to be taken into account using the PRADO software:

- The PRADO software only allows for 10 different sieve sizes at a time, while the 26.5mm max BTB mix requires 11 sieves. Therefore in defining the COLTO specifications for BTB continuously graded 26.5mm max size in PRADO one sieve had to be left out. After studying the grading envelope it was decided that the limits on the 0.600mm sieve have the least influence on the grading curve and have therefore been left out;
- PRADO uses the lime filler as a normal aggregate component and calculates the optimum usage of this fraction, without limiting the active filler to a certain percentage;
- Certain assumptions have to be made regarding the loss of fines through the plant. In the analyses below it has been assumed that no loss of fines occurs in the plant.

From Table 2 it can be seen that in all cases the PRADO approximations of the designs result in similar component compositions and thus in similar gradings. The PRADO optimum BTB 109-57 composition however is slightly different than the composition for the MUCH BTB 109-57 design. The PRADO optimum grading is a better approximation of the middle of the grading envelope (a mix with such a grading is not necessarily a better performing mix), especially on the smaller sieves. However, the 19.0mm fraction remains outside the specified limits and it appears as if with the given aggregate fractions it is not possible to comply with the limits for the 19.0mm sieve opening.

The PRADO optimum BTB 109-57 uses 4.3% of the lime fraction, which is obviously more lime than required. As mentioned above, no limits can be set on the use of certain aggregate components in the PRADO optimization process. One could however only use 1% lime and find replacing filler for the remaining 3.3%. The same applies for the PRADO optimum TRH8 composition, which is calculated to use 2.6% lime.

It can be seen in Table 2 that when the composition of aggregate components to obtain the design gradings is compared with the composition to obtain the PRADO optimum gradings, there are quite substantial differences. For instance, if the BTB 109-57 is considered it can be seen that the PRADO optimum composition uses more of the 19.0mm fraction, less than half of the 13.2mm fraction, more than twice as much of the 9.5mm fraction and nothing of the 6.7mm fraction (compared to 5% for the MUCH design). In case of the wearing course mix, it can be seen that the quantity of 13.2mm stone required for the PRADO optimum TRH8 is substantially less than for the MUCH TRH8 design (11.9% vs. 18%). Also the required crusher sand fraction increases by 6.8%.

3.3 Volumetric Properties

The volumetric properties as determined by PRADO are summarised in Tables 4 and 5. The volumetric properties according to the Marshall design are also included in these tables. The optimum binder contents have been determined based on a 4% required void content. As can be seen the VMA calculated by PRADO does not change for varying binder contents. This is probably the result of the fact that PRADO calculates the VMA based on grading and compaction energy level only. The quantity of bitumen added does however influence compaction because of the lubricating effect of the binder. Therefore the VMA at a certain compaction energy level should not be constant for changing binder contents. Normally the VMA reduces at increasing binder contents to a certain minimum, after which the VMA increases again.

It can be seen that the VMA's as calculated by PRADO are very close to the VMA's determined in the Marshall test. For the asphalt base mix the VMA's calculated by PRADO are either slightly lower, equal to, or slightly higher than the VMA's determined in the Marshall tests and never differ more than 0.8%, depending on the binder content and the analysed case.

For the analysed wearing course cases it can be seen that the VMA's determined by PRADO are always slightly lower, but never differ more than 0.8%, than the VMA's determined in the Marshall test. At a binder content of 5.0% the VMA of the asphalt base mix was 13.7% in the Marshall test and 13.8% according to PRADO. For the wearing course mix these values are 16.4% and 15.7% respectively. Because the VIM and VFB relate directly to the VMA, the same differences between the VIM's and VFB's determined by PRADO and in the Marshall test occur.

Optimum binder contents have been determined for the PRADO mixes based on 4.0% voids in the mix. For the PRADO optimum BTB 109-57 mix this resulted in an optimum binder content of 3.8%. According to the Marshall test this would be 3.9%. The binder required to achieve 4% VIM as determined by PRADO is therefore slightly lower than as determined by the Marshall test. The other two mixes analysed (PRADO approximation of MUCH design grading BTB 109-57 and PRADO approximation of MUCH design grading BTB 109-57, Olies + RK) have optimum binder content of 4.05% and 4.00% respectively.

For the wearing course mix a binder content of 4.8% would be required according to PRADO to obtain 4% VIM, while in the Marshall test this is 5.05%. For both mixes, the binder contents at comparable voids contents (4.0%) are therefore approximately 0.2 – 0.3% lower. Although the grading of the two analysed wearing course mixes differs substantially, the volumetric properties calculated by PRADO are almost identical (Table 5). While the differences between the gradings of the analysed asphalt base mixes are much smaller, the difference in volumetric properties is larger (see Table 4).

Table 4. Marshall and PRADO volumetric properties for the asphalt base mix.

		Binder content					
		3.5%	4.0%	4.5%	5.0%	4.3%	o.b.c
VIM	Marshall	5.7	3.9	2.1	1.6	2.82[1]	
	PRADO 1	4.71	3.48	2.26	1.04	2.75	3.97
	PRADO 2	5.32	4.11	2.90	1.68	3.38	3.99
	PRADO 3	5.27	4.04	2.81	1.58	3.30	4.04
VMA	Marshall	14.1	13.6	13.3	13.7	13.4[1]	
	PRADO 1	13.3	13.3	13.3	13.3	13.3	13.3
	PRADO 2	13.8	13.8	13.8	13.8	13.8	13.8
	PRADO 3	13.9	13.9	13.9	13.9	13.9	13.9
VFB	Marshall	59.6	71.6	84.3	88.0	81.7	
	PRADO 1	64.5	73.7	83.0	92.2	79.3	70.1
	PRADO 2	61.5	70.3	79.0	87.8	75.5	71.1
	PRADO 3	62.0	70.9	79.8	88.6	76.2	70.9
f:b (m/m)	Marshall	1.9	1.7	1.5	1.3	1.6	
	PRADO 1	2.37	2.07	1.84	1.66	1.93	2.18
	PRADO 2	1.74	1.53	1.36	1.22	1.42	1.51
	PRADO 3	1.74	1.53	1.36	1.22	1.42	1.53

1) Values are derived by interpolation
Marshall: Marshall design, optimum binder content 4.3%
PRADO 1: PRADO Optimum BTB 109-57, optimum binder content 3.80%
PRADO 2: PRADO approx. of MUCH design grading BTB 109-57, optimum b.c. 4.05%
PRADO 3: PRADO approx. of MUCH design grading BTB 109-57 Olies + RK, o.b.c. 4.00%

Important factors in the determination of the VMA by PRADO are the density of the aggregate, the angularity, the Rigden voids of the filler, the binder properties and the applied compaction energy. In terms of angularity PRADO calculates with either 'round' or 'angular' aggregates, without the option to enter a partial angularity. All analyses described in this paper have been carried out assuming 'angular' aggregate. Some initial problems were encountered in determining the Rigden voids of the filler and subsequent measurements showed a lower Rigden voids than initially determined. A value of 29.7 for the Rigden voids was used in the analyses. No sensitivity analyses has been carried out to determine the effect of changes in the above parameters on the volumetric properties (VMA) determined by PRADO.

Table 5. Marshall and PRADO volumetric properties for the wearing course mix.

		Binder content					
		4.5%	5.0%	5.5%	6.0%	4.9	o.b.c
VIM	Marshall	5.4	4.1	2.5	1.7	4.4	
	PRADO 1	4.79	3.57	2.36	1.14	3.81	4.06
	PRADO 2	4.72	3.50	2.29	1.07	3.75	3.99
VMA	Marshall	16.4	16.4	16.0	16.5	16.4	
	PRADO 1	15.7	15.7	15.7	15.7	15.7	15.7
	PRADO 2	15.7	15.7	15.7	15.7	15.7	15.7
VFB	Marshall	66.8	75.2	84.7	89.6	73.5	
	PRADO 1	69.6	77.3	85.0	92.7	75.7	74.2
	PRADO 2	69.9	77.6	85.4	93.2	76.1	74.5
f:b (m/m)	Marshall	1.0	0.9	0.8	0.8	0.9	
	PRADO 1	1.57	1.41	1.29	1.18	1.44	1.47
	PRADO 2	1.11	1.00	0.91	0.83	1.02	1.04

Marshall: Marshall design, optimum binder content 4.9%
PRADO 1: PRADO optimum TRH8, optimum binder content 4.8%
PRADO 2: PRADO approx. MUCH TRH8 design, optimum binder content 4.8%

The level of compaction energy in PRADO can be set in the range of 96% up to 102% of standard Marshall compaction. Although in South Africa 2 x 75 blows with the Marshall hammer is standard compaction, in Belgium this is 2 x 50 blows. Therefore in PRADO the level of compaction energy should be set to 102% in order to be able to compare with South African laboratory Marshall design test results. All analyses described in this paper have been carried out at the 102% level. A lower compaction energy level (i.e. 100%) results in VMA's that are 2 – 3% higher.

4. CONCLUSIONS

4.1 Grading and Component Composition

PRADO is a useful tool when analyzing an aggregate grading of an asphalt mix and the fractional composition thereof. As can be seen from Table 5 the PRADO approximations of the mix designs result in similar gradings and compositions for the two asphalt base mix cases as well as for the wearing course mix case. PRADO can therefore be used to check and confirm design gradings and their composition.

Where the PRADO analysis becomes more useful is where several possible grading curves (which may differ from each other but still all fall into a permissible grading envelope) are compared with each other. In this analysis the MUCH design gradings (that are not in the middle of the grading envelope) were compared with gradings that lie in the middle of the grading envelope. The first aspect of this comparison is that the difference in aggregate composition can be analysed. As can be seen in table 2 the usage of the individual aggregate fractions can differ substantially (compare MUCH design grading composition and the PRADO optimum composition). Such analyses could be used in the optimisation of bin settings at an asphalt production plant or to economise on certain aggregate fractions. However, in this PRADO is not unique and there is other software and spreadsheet programs available that can carry out similar analyses and optimisation.

One has to bear in mind that there are a number of grading curves that can be fitted into grading envelopes as those specified in COLTO and TRH8 that differ substantially in composition and eventually in behaviour of the asphalt mix. Where PRADO becomes a powerful tool is where the results of the grading analyses are combined with the binder properties and subsequently the volumetric properties of the asphalt mix are predicted. In this manner one can easily analyse what the influence of a difference in grading is and what effect it has on VMA and voids.

4.2 Volumetric Properties

It is noted that the VMA's as calculated by PRADO are comparable to the VMA's determined in the Marshall tests. The VMA in PRADO does however not change with varying binder contents. For both the wearing course mix and the base mix it has been found that the difference between the VMA as determined by PRADO never differed by more than 0.8% from the VMA determined in laboratory Marshall tests. The difference in VMA has an effect on all the other volumetric parameters (VIM, VFB) as they are dependent on the VMA. No sensitivity analyses have been carried out for the parameters influencing the determination of the VMA by PRADO. It is recommended that in future this research is extended to include such analyses.

The binder contents to obtain a 4% VIM level in PRADO are equal to the binder contents in the Marshall test. Only slight differences, less than 0.2%, were found.

There is little difference in the volumetric parameters determined by PRADO for the two wearing course cases analysed (PRADO approximation MUCH TRH8 design and PRADO optimum TRH8). This is remarkable as for these two cases the gradings differ substantially.

While the difference in gradings for the two asphalt base cases (PRADO approximation MUCH BTB 109-57 design and PRADO optimum BTB 109-57) is much less then is the case for the wearing course equivalents, the effect on the volumetric properties is much larger.

4.3 General Comment

Although differences in volumetric parameters were found between the results of the Marshall test and the PRADO analyses, these differences were generally small and consistent throughout all parameters.

The authors of this paper have limited experience in desktop mix evaluation using PRADO and more studies similar to this one would need to be carried out in order to be able to correctly qualify the findings of the PRADO analyses and correctly judge them in relation to the well known and proven Marshall test parameters.

Nevertheless it can be concluded here that the PRADO analyses have shown some interesting results and are particularly useful when evaluating the influence of slight differences in gradings and aggregate compositions on the volumetric parameters of an asphalt mix. Without having to go through a more costly and time consuming process of laboratory mix design tests, alternative designs can be explored using a desktop tool such as PRADO. If promising alternatives are found these would still need to be validated by laboratory tests, but by using a desktop mix design tool the laboratory mix design procedure can become more efficient.

5. REFERENCES

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BIOGRAPHY

Lucas-Jan Ebels graduated in 1998 at the Delft University of Technology in the Netherlands (MSc Eng in Pavement Engineering). Part of his Master's Study was carried out at the University of Stellenbosch and covered research on the labour intensive manufacture of bitumen stabilised paving blocks.

After a short period of employment at the Netherlands Pavements Consultants, Lucas-Jan moved to South Africa in 1999 where he worked for 3 ½ years for UWP Consulting in the Eastern Cape, where he did design and contract supervision of numerous gravel roads and was involved in some major National Road projects.

In October 2002 Lucas-Jan started a full-time PhD study at the University of Stellenbosch under promoter Prof Kim Jenkins. His PhD research is focussing on the behaviour and properties of cold asphaltic mixes (foamed bitumen and emulsified bitumen mixes).